Simulation Modeling of Hypotheses for African Development

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Simulation Modeling of Hypotheses for African Development

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I. Introduction

The simulation model presented here is a hypothesis concerning basic ecological-economic relationships in Africa. The model was developed over the course of several months in a series of meetings with experts convened by the U.S. Agency for International Development, Africa Bureau, Office of Sustainable Development (AFR/SD). The purpose of this group modeling exercise was to draw out and review some of the less well-recognized, or more newly recognized, relationships among ecological and economic variables in Africa. The model was written in a systems dynamics modeling environment using the STELLA simulation modeling package.

The iterative approach of meetings, discussion, and model development is central to the process of forming and reviewing these hypotheses. The model expresses a basic understanding of ecological-economic relationships, and provides a point of focus for the conversation among interested experts. The conversation then informs the process of model development. In this way, insights that follow from the model at one stage of development spur further insights that inform its further development.

The emphasis in this systems model is on the causal relationships among variables, rather than the statistical relationships. Shifting the focus to these causal relationships is one way to help get around the limitations of data availability. The focus on causal relationships allows us to include important qualitative, or “soft” variables in development hypotheses: knowledge, concern over the status of natural resources, gender-related access to capital, and other variables that are difficult to measure or express in quantitative terms. The models, and the process of model development, are particularly useful for designing and illustrating hypotheses about how certain variables are related to one another. They are also useful for developing scenarios – answers to “what-if” questions concerning the ecological-economic system in question. These future scenarios are not predictive, but provide one way to test the assumptions or hypotheses that make up the model. They are complements to, not substitutes for, stochastic models incorporating traditional indicators.

Systems models constructed through this iterative process can be used as a way to develop consensus among a group of interested individuals concerning the basic ecological-economic relationships in a given area. When used this way, it is the process of model building, and the conversations that are involved, that are especially useful, sometimes more so than the final model. The final simulation model may be an end in itself, or its development may be a means to formally express, review, and develop hypotheses about these linkages.

Developing the model requires formally expressing one's basic understanding of underlying ecological-economic linkages, and facilitates its review. As in this case, when the modeling process involves a group, the objective at this point is to state these basic understandings of these linkages and put them down on the page in a systems diagram, where the diagram establishes a formal structure of stocks, flows, and related variables. The formal structure of the simulation model brings a certain discipline to the conversation about these linkages, and makes it easier to identify points of agreement, and differences in basic understanding.

Reviewing, revising, and expanding these scoping models can continue indefinitely, just as the traditional approach toward indicators and their statistical relationships does. The advantage of developing scoping models as a group effort is that it brings in a formal structure for reviewing these basic relationships, where the continuing development and review of these models leads to new insights that might not otherwise arise. These scoping models have a high degree of generality, that is, the relationships they reflect can often be applied broadly, and at many scales.

Developing a research or management model in a systems modeling framework involves increasing the resolution beyond that of a scoping model. Adding these details tends to make the model more realistic, but the details make the model less generally applicable; a research or management model is more site-specific than a corresponding scoping model. The model presented here is a scoping model. In developing these models, it is important to recognize that there is a tradeoff between resolution (detail; complexity) and predictability (Costanza and Ruth 1998). Increasing the degree of detail in a systems model may approximate more details about the real-world system, but predictive power of the model tends to fall with the increase in resolution. If your primary objective is accurate short-run prediction of traditional indicators, consider a multiple regression rather than a systems model.

Readers who are interested in a more detailed understanding of the differences between these two modeling approaches, and the relative advantages of each, are encouraged to read "Dynamic modeling of ecological-economic systems: An introduction for International Resources Group and the United States Agency for International Development Africa Bureau," April 11, 2000, by this author (Woodwell 2000). The document is available on the FRAME website. The model presented here, and the conversations that generated it, follow from that introduction.

The immediate purpose of this modeling exercise was to draw out some important, but less well-recognized ecological-economic relationships in Africa. In drawing a few bold lines through the tremendously complicated and intricate challenge of African development, we hope to add some more insights to the discussion on development hypotheses in Africa. In addition, a broader and equally important purpose of this exercise is to introduce a tool and a process for expressing, amending, and reviewing further development hypotheses.

The importance of the participatory component of this modeling effort should not be understated. Involvement of several interested experts on natural-resource related issues in Africa generated an immediate built-in peer review process for concepts and ideas that came out in the workshops. The diverse background of the experts and the iterative modeling approach means that each expert can contribute to a different part of the model and get rapid feedback from other participants. This process of model development is partly a process of recording, in the formal syntax of a systems dynamics modeling environment, the mental models that we develop over the course of years. These models reflect our collective experience, and putting them down on the page in a participatory systems dynamics framework makes it easier to evaluate them, expand and review them, and communicate them to one another. The formal modeling environment helps to increase our capacity to review and expand these mental models. In this model, the principles that are expressed are principles that may be applied broadly to issues in African development. The scenarios the model yields should not be viewed as predictions, but as scenarios that illustrate hypothesized relationships among variables.

Participants in one or more of the roundtable discussions include Paul Bartel and Mike McGahuey, USAID/AFR/SD; Henri Josserand, Associates in Rural Development; Max McFadden, Bruce Miller, Kathy Parker, and Mike Saunders, The Heron Group; Bob Winterbottom and Asif Shaik, IRG; Yves Prevost, the World Bank; and the author. The model and this report are solely the responsibility of the author.

Published literature, reflected in the expertise of the roundtable participants, in part forms the basis of this inquiry into development hypotheses. The simulation model developed in this effort is a general model, one that seeks to incorporate principles that can be applied broadly to many challenges of African development, and at many scales. The corresponding challenges in the field also occur at many levels of detail, including individual households, communities, and regions within Africa.

The model was developed in a series of steps, first as a simple natural capital mining feedback representing resource consumption or depletion to meet basic human needs. That model is the Simple Economy model of Woodwell (Woodwell 2000). Then, a subsequent version of the model incorporates technological development, both as an increase in the efficiency with which natural capital is used, and as an increase in the capacity to mine natural capital. Also added to the model is the potential to invest in natural capital. These changes to the model yield scenarios where it is possible to mine natural capital in some cases, and spiral downwards as consumption of capital reduces future income, and thereby spurs further mining; and invest in natural capital in other cases, and thereby increase future income and increase the potential to make further investments. Further expansion of the model yields the full Primary Economy model incorporating seven sectors. In this paper, issues in African development are discussed, then details of the models, and finally model runs.

II. Issues in African Development

The challenge of African development includes raising living standards immediately, while reversing degradation and depletion of natural resources so as to maintain those standards into the future. This paper addresses aspects of the economy-environment linkage, and some possible (including some demonstrated) ways to raise living standards. Two major themes – improving the efficiency with which natural capital is used, and investing in natural capital – are reviewed in the context of selected cases, and expressed in the series of simulation models.

There are many demonstrated cases of increased technological efficiency in Africa. Masters et al. (Masters, Bedingar et al. 1998) reviewed 32 case studies of African agricultural research. These studies are mostly reports, not widely published, written for specialists in particular countries. They are not a random sample, but do include a broad cross-section of research programs. All but 8 studies reported annual rates of return on investment in excess of 20%. In these reviewed cases, the increased yields were due to various causes including introduction of new species that mature rapidly to reduce weather-related risks, notably drought. Other improvements included methods of retaining soil moisture and fertility. The emphasis on a financial return on investment again raises the question of potential mining of natural capital, and the difficulty in measuring it – a relationship illustrated in the overshoot-and-collapse scenarios of the early Simple Economy model (Woodwell 2000). As to whether these studies are measuring true, sustainable increases in productivity, or whether they are counting as income some mining of natural capital, remains an open question.

Published research on agriculture in Rwanda shows declining yields linked to erosion of soil (Clay 1995; Byiringiro and Reardon 1996). Several variables feed into the cause of soil loss, including growth in population that drives agriculture onto steep slopes. Further trends include fragmentation and shrinking size of land holdings, and replacement of fallow periods with longer periods of cultivation (Ford 1993; Clay 1995; May 1995). This circumstance characterizes the right-hand end of the model runs dominated by mining of natural capital, where the lack of investment in natural capital, and a declining resource base tighten a downward spiral of depletion and declining income.

Clay et. al (Clay, Reardon et al. 1998), in a review of the efforts to reverse these trends, and distilling the work of Boserup, characterize two approaches: “capital-led” agricultural intensification, and “labor-led” agricultural intensification in Rwanda. The capital-led approach involves increasing physical inputs – manure, mulch, and composting as organic fertilizer; grass strips, hedgerows, and terracing as direct erosion control measures; and chemical fertilizers and pesticides. Clay et. al add the planting of perennials as a potential option within the capital-led intensification path. The labor-led approach involves only an increase in the labor component of agricultural production. This increase in labor may include more intensive cultivation, shorter fallow periods, or more intensive weeding.

The capital-led intensification path must also employ labor to make use of the physical capital. Similarly, the labor-led path must employ some physical capital, if only for tools, so there is not a perfect division between these two paths, but a spectrum of alternatives between them. The necessity of labor to employ the physical capital for these investments in natural capital points to the complementarity of labor and physical capital. This complementarity in turn raises the possibility that when either form of input – physical capital or labor – is in tight supply, investment in natural capital may be impeded. The model addresses both possibilities. In the case of labor, the opportunity cost of one's time indicates the value of applying one's efforts to alternative tasks, one indicator of the scarcity of labor. The higher the opportunity cost of one's time, the more scarce is labor for investment in natural capital. Stated otherwise, labor for investment in natural capital is more expensive and more scarce when there are higher-paying alternative employment opportunities for those workers. In the case of physical inputs, materials scarcity is addressed in the context of income relative to a subsistence income. When income is in excess of a subsistence level, there is the possibility within the model of investing a part of the surplus in physical inputs for development of natural capital.

In the case of the Rwandan highlands, the empirical evidence on capital-led intensification reported by Clay et. al (Clay, Reardon et al. 1998) indicates that the labor-led intensification path may increase total yields in the short run, but tends to lead to soil erosion, loss of soil fertility, or more generally, to the erosion, mining, or depreciation of natural capital. This depletion is not sustainable. The capital-led intensification path has been more successful at improving long-term yields by reducing soil erosion and increasing soil fertility. The empirical results of the Clay et. al analysis are interesting and worth reviewing in some depth, although the results are also generally not surprising. Organic fertilizer inputs tend to reduce erosion and are correlated with chemical fertilizer inputs and investments in improved cropping patterns and other erosion control improvements. These improvements occur mostly on slopes of intermediate steepness, where the payoff is the greatest. The dearth of capital-led intensification on the steepest slopes is a reflection of the high cost of investments there, and the difficulty in maintaining those investments.

Physical and economic factors appear to be more important in spurring capital-led agricultural intensification, rather than just knowledge of sustainable practices in the Rwandan highlands. However, Clay and Reardon (Clay and Reardon 1994) do find that in cases where a new technology is introduced, knowledge of the technology tends to spur its adoption more than knowledge of more traditional, generally better known, conservation investments. In the Rwandan highland case, farmers who are familiar with conservation and fertility-improving technology tend to plant hedgerows more than other farmers. Whether the adoption of the new technology spreads as a result of knowledge alone, or whether the new technology is more productive than traditional, better known investments, remains an open question.

One factor that plays into this relationship is a certain tendency to adopt the practices of one's neighbors. Clay et. al (Clay, Reardon et al. 1998) note the "local area" effect of capital-led intensification, where farmers effectively borrow ideas and experience from those around them. Thus, a technology that is successful in a given area will tend to be adopted by others in the area, and if other conditions are suitable, will tend to spread autonomously until a certain saturation point is reached. An open question concerning this relationship is whether the growing adoption of intensification technology under these circumstances constitutes spreading knowledge of the technology in a pure sense, or whether the growing adoption reflects a growing confidence in the technology, and thus a reduction in risk. The relationships are treated as risk-related in the Primary Economy simulation model, where probabilities of recovering the investment (plus some extra) are weighed against the risks of losing at least part of it.

An additional variable that affects progress of capital-led intensification is the opportunity cost of one's time. To the extent that capital-led intensification is also labor-intensive, that is, to the extent that capital and labor are complementary, a high cost of labor has the potential to dampen capital-led intensification. There is the possibility of a feedback where capital-led intensification eventually increases incomes to the point where investments elsewhere in the economy make alternative employment more profitable than the employment required for capital-led intensification. If the feedback holds, then increased productivity from capital-led intensification tends to raise wages, making capital-led intensification more expensive, which in turn reduces the intensity of agricultural management, and may lead to increased degradation. Clay et. al (Clay, Reardon et al. 1998) found evidence of a small part of this feedback in the Rwandan highlands case, where a higher nonagricultural wage reduces the use of organic matter in soil. This particular feedback may be limited to particular cases within certain income levels. It also may depend on the degree to which increases in income are a result of capital-led agricultural intensification, vs. other non-agricultural causes. Kelly (Kelly 2000) found that in the Office de la Haute Vallée du Niger (OVHN) zone of Mali, capital-led intensification coupled with diversification toward revenue-generating systems led to greater prosperity and to reduced rates of degradation.

Risk of appropriation of land appears to enter into the equation as well. In the Rwandan highland case, Clay et. al (Clay, Reardon et al. 1998) note that households are far less likely to grow perennials on land they rent than on land they own. It is possible that tenant farms have not had sufficient time to invest in perennials, or whether the rarity of perennials on rented land reflects a deeper concern over land tenure. This relationship enters the Primary Economy model as risk-related variables in the risk sector.

The Machakos District of Kenya offers an interesting case-study of agricultural development (English, Tiffen et al. 1994; Tiffen, Mortimore et al. 1994). The case-study is unusual in that it covers an unusually long period for a case-study, from the 1930s to the 1990s. In the 1930s, the Akamba people of the Machakos District, effectively hemmed in by Crown Lands and lands reserved for European settlement, grazed and cultivated their available lands intensively and in a way that yielded rampant soil erosion and a bare subsistence living.

During the 50+ years of reviewed experience in the Machakos District, agriculture shifted from primarily livestock herding with limited cropping for personal consumption, to primarily the growing of crops, a significant part of which was sold (English, Tiffen et al. 1994). Over the decades, as crops replaced livestock, the Akamba adopted terracing, first narrow terraces that were awkward to use with draft animals, then wider “bench” terraces. The varieties of crops changed over time, initially coffee and cotton, with a shift to fruit and horticultural crops as their relative prices changed. Other innovations included ox-drawn plows, early-maturing varieties of maize, use of crop residues for forage, and use of animal manure in soil (English, Tiffen et al. 1994).

Over the period of the study, the human population in the area as a whole grew by a factor of five, the area under cultivation grew by roughly a factor of five, and the estimated value of agricultural production per capita grew by a factor of three. The expansion of agriculture came at the cost of natural bush and scrub (English, Tiffen et al. 1994).

With more than 50 years of observation, the case-study is one of the longer ones. The positive trends of increased income over that time period, and reduced rates of soil loss, suggest a transition to a more sustainable agricultural economy. Continuing soil loss coupled with analyses showing that the fertility of the soils is less than that of soils under natural vegetation suggest that agriculture on the whole has led to degradation. However, there does not appear to be evidence that fertility has continued to decline (English, Tiffen et al. 1994).

Several aspects of the Machakos experience are reflected as relationships within the Primary Economy model. Land tenure, in the risk sector of the model, is strong in the Machakos District, and flows from the freehold customs of the Akamba. Risk related to social stability are similarly low, so those two factors do not appear to hinder investment in natural capital. Diversification comes partly as a result of knowledge introduced by government in the form of new crops. Similarly introduced soil conservation techniques including terracing spur investment in natural capital, and thereby increase income.

The authors of the case study note that the new market orientation of agriculture has increased its perceived value, and provides an incentive to maintain systems that permit continued intensive use of the land. This relationship is reflected in the status of capital sector of the Primary Economy model, where an understanding of the connection between maintenance of natural capital, and continued productivity of that capital, come together into local concern over the status of natural capital. It is that understanding – maintenance of the natural capital stock is necessary to maintain agricultural output – that leads people to reinvest in natural capital and technology to increase productivity.

The Machakos case may fit at least two major scenarios that the Primary Economy model yields. The first is the "climb-out" scenario, where a one-time investment in technology and natural capital from outside sources pushes income up sufficiently to produce a surplus that is then reinvested. In this way, the Machakos District, over a period of several decades, moved from the downward spiral of natural capital mining and declining true income into the upward spiral of investment and rising true income. The shift from the downward to the upward spiral reflects both new technology – specialized crops and improved techniques – and direct investment in natural capital – return of manure to the soil, and other measures to maintain its productivity or otherwise reverse depletion.

When explaining the increased prosperity of the area, the authors of the case study (English, Tiffen et al. 1994) argue that the agricultural growth has accompanied a stabilization of the resource base. The possibility remains open, however, that slow, more subtle depreciation of natural capital is still working against long-term sustainability of agricultural production. The challenge of finding sensitive and reliable indicators is notable here. The degree to which agricultural output is being fueled by mining of natural capital, such as the continuing soil loss (although at lower rates than previously), is still an open question. Also, the longer-term trend in nutrient levels is also an open question. Although a 50+ year time frame is long for a case study, it may not be sufficiently long to anticipate trends for the next 50+ years. Reardon and Shaikh (Reardon and Shaikh 1998) touch on a similar principle concerning mining of natural capital, noting that International Resource Group's analyses in the Sahel indicate that current agricultural production is being maintained only by progressively depleting soil nutrients. Similarly, research with the Senegalese Agricultural Research Institute shows that increasing crop density of peanuts without applying manure and fertilizer is depleting the soil there, at the cost of future harvests.

A further important factor that has bearing on investment in natural capital, in addition to land tenure, is availability of monetary capital. In both cases, the evidence indicates that gender and land tenure have bearing on access to capital and play important roles in securing loans. USAID (USAID 1992) found that women confront greater obstacles to securing credit than do men. Financial institutions tend to offer loans to those with sufficient capital or collateral, and to larger projects that do not necessarily fit women’s needs, a case documented in certain savings and credit cooperatives in Nigeria (Bhatt 1989; Green and Thrupp 1998). The problem is compounded when traditional land tenure systems recognize men’s ownership of land, not women’s, making it difficult for women to use land as collateral for loans (Green and Thrupp 1998).

The challenge of women’s limited land tenure rights and access to capital become more pronounced when men move from rural to urban areas in search of work, leaving women as head of households, and as gender ratios are skewed as a result of HIV/AIDS. The gender ratio enters the Primary Economy model in two ways – as a factor affecting tenure, and therefore risk, and as a factor affecting access to capital. Access to capital has bearing on investment in natural capital, but it also may open up the possibility of getting a better price, and a better return, for agricultural products. To the extent that capital constraints force immediate or premature sale of agricultural products, access to capital can offer some extra breathing room to sell (or buy) at more favorable times.

The concept of poverty employed in the model is somewhat different from an income-threshold criterion or other standard of welfare. Rather, the criterion employed in the model is whether there is sufficient income to invest a surplus. Reardon and Vosti (Reardon and Vosti 1995) call this distinction the difference between “welfare poverty” and “investment poverty,” and note that households or villages above a welfare-determined poverty line may still be too “investment-poor” to make improvements in their resource base or otherwise build up productive capital. The welfare-standard approach is particularly useful for indicating immediate conditions of well-being, or human misery. Criteria for a welfare-poverty approach many include an estimated caloric intake, or income sufficient to provide a certain diet.

In contrast to the welfare-poverty approach, the Primary Economy model employs an investment standard where the critical factor is the availability of surplus income for investment. While the welfare poverty standard helps to highlight immediate human conditions, the investment poverty standard helps to highlight the capacity (or lack thereof) to climb out of poverty. The investment standard directs light toward the nature of, or severity of, the poverty-environment link. There may be several dimensions of investment poverty. Market conditions, legal conditions, or physical conditions, may preclude investment in natural capital; investments may be prohibitively expensive; there may not be sufficient knowledge within a household or community to make particular investments; or households may prefer to use surplus income for consumption, rather than investment.

Fenwick and Lyne (Fenwick and Lyne 1999) found a host of impediments to investment in small-scale farming in KwaZulu-Natal. These impediments go beyond the constraint of surplus income and include poor access to land, low availability of labor, lack of information and knowledge about potential for increasing productivity, and high transaction costs. The authors argue that in order to create conditions where investment in increased agricultural productivity is productive, investments in literacy and language skills, vocational training, and business and management skills is necessary first, and even larger challenges of improved roads and the further development of legal institutions stand in the way of full realization of the potential for investment in agricultural productivity.

Access to credit for investment can be an important determinant of investment. The availability of collateral for a loan can in turn be an important determinant of access to credit. Reardon and Vosti (Reardon and Vosti 1995) observe that the specific nature of a household's or community's assets, not just their total value, may in part determine a family's access to credit. If productive land is the collateral to get credit, and a household has little land, or especially poor land, it may be difficult to garner the credit necessary to make investments in improving management of the soil. These details of the particular nature of a household's assets may have bearing on the potential for investments in natural capital.

III. Developing a Primary Economy Model

The following graph is output from the Simple Economy model of Woodwell (Woodwell 2000), and illustrates a scenario of long-run overshoot and collapse. In this model, the economy is supported entirely by mining of natural capital. One way to interpret the graph is to first cover the right-hand side of it, so that the data show a nominal 50-year time frame. Mining of natural capital supports GDP, both of which generally rise over time. The trend of rising, or at least nondeclining, GDP suggests at least a component of successful development.

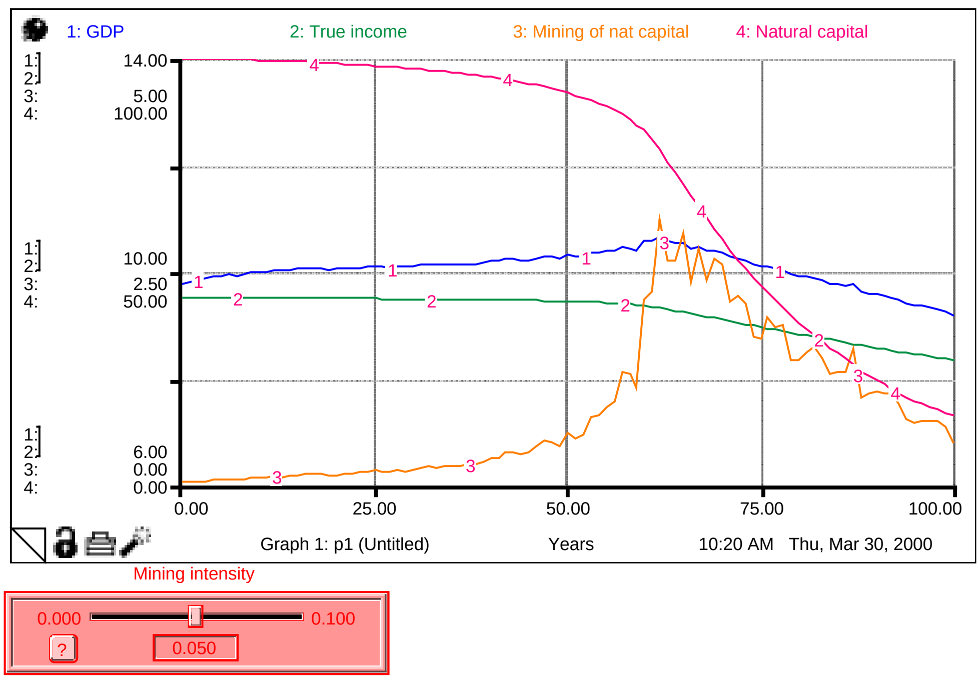

Figure 1: Simple Economy model showing an overshoot and collapse scenario

However, true Hicksian income is sustainable income: income that does not reduce future income. Stated otherwise, true income is that which is drawn from a nondeclining stock of capital, natural capital in this example. True income is easy enough to define, but much more difficult to measure in the real world. So although the graph shows nondeclining GDP, commensurate with the mining of natural capital, this GDP is not true income. Rather, as shown on the graph, true income declines slowly over time as the stock of natural capital is mined. Although the relationship is clear enough in the graphical output of the model run, the relationship may be much more subtle in the real world. In many real-world cases in Africa, where natural capital is being mined or depreciated, it may not be possible to measure true, sustainable income at all.

The collapse scenario is illustrated in the right-hand side of the graph, where the decline in the stock of natural capital necessitates greatly increased mining to support GDP. The mining of natural capital reduces that stock further, which in turn leads to more mining to support GDP. This positive feedback ultimately leads to a collapse of natural capital, which in turn causes the collapse of the other three variables.

The two distinctly different trends illustrated in this collapse scenario point to the importance of the time scale used in describing the trends, and to the importance of including variables that are hard to observe. In this case, those variables include true income, and mining or depreciation of natural capital. During the first half of the model run, the most easily observed variable (GDP) indicates increasing prosperity. The remaining variables, all of which are more difficult to observe or measure in the real world, hint at a different story. In the second half of the model run, the declining GDP indicates a problem, but by the time GDP starts its downward trend, the outlook for less-easily observed variables is not good.

These less-easily observed variables, or “soft,” or “qualitative” variables, are especially useful for anticipating more general trends. The traditional indicator of GDP is easier to observe, but there is a time lag between trends in the soft variables and trends in the more easily observed of GDP. The trends in the soft variables of the first half of the graph provide and indication of what may be coming for GDP at a later time. The foresight flows from a hypothesis about the relationships among these soft variables, which, when expressed in the formal structure of the simulation model, yields a scenario with insights that help extend those that employ only traditional indicators.

Adding Technological Development

The overshoot-and-collapse scenario of the Simple Economy model is driven by the mining of natural capital. There is no provision within the model for investing in natural capital, or otherwise augmenting it, and there are no technology linkages within the model. The first modification involves introducing technology to the system.

In the following diagram, certain linkages to technology are included. In this model, technological development can do one or both of two things: it can increase the capacity to mine natural capital, and it can increase the efficiency with which the services of natural capital are provided. The first form of technological development involves, in effect, increasing the economy’s capacity to take bites of natural capital, and use them as income. The second form involves increasing the productivity of natural capital, so that each unit of capital yields more income. The first case could be a larger car, where the second case could be a more efficient car; or agricultural technology that tills more soil and thus exposes more soil to erosion, vs. agricultural technology that disturbs the soil less while maintaining crop yield.

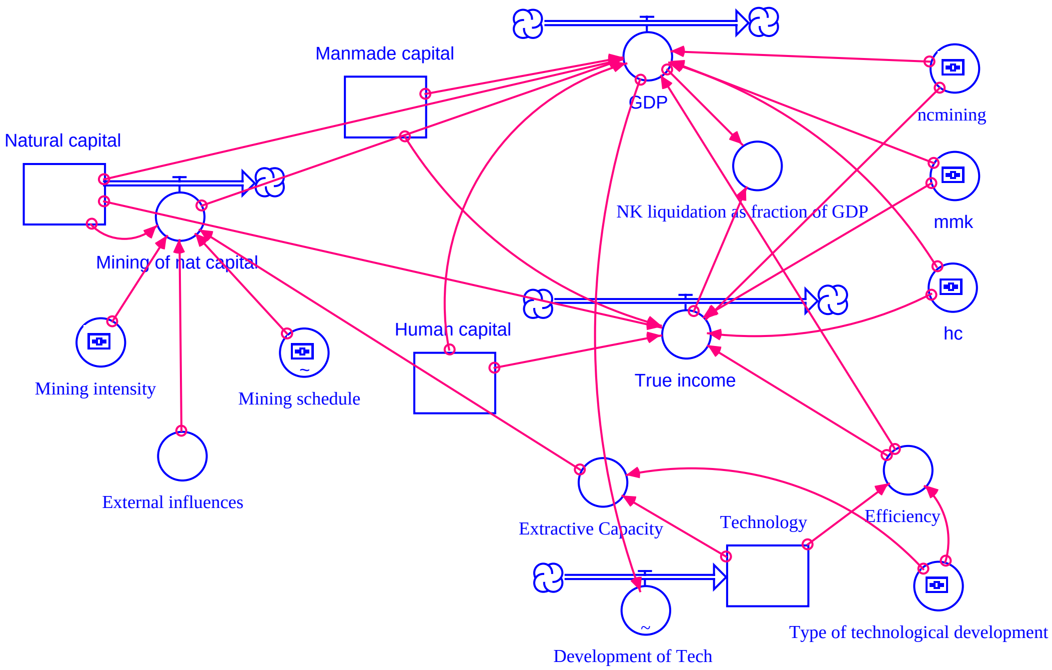

Figure 2: Simple Economy model with technology added

The type of technological development can be controlled within the model. It can be directed entirely toward increasing the capacity to mine natural capital, entirely toward increasing the efficiency with which natural capital is used, or toward any mix of the two. In the following scenario, the run starts with technological development directed toward increasing the capacity to mine natural capital, and then gradually shifts toward increasing the productivity of natural capital. As in the run with no links to technology, true income falls at first as natural capital is mined, but then as technology is steered toward improved efficiency, and as the rates of mining are reduced, true income rises along with GDP. There is still some mining of natural capital, and the stock of natural capital does decline, but not as fast as technology increases the productivity of natural capital.

This case is one variation of a so-called soft sustainability scenario, where increased efficiency in a sense makes up for the loss of natural capital (Pearce and Turner 1990; Pearce and Atkinson 1993; Daly 1994). In agricultural intensification, additions of other inputs such as fertilizer and labor increase the productivity of the limited input, land. The new recombination of inputs can be viewed as a technological development. If the inputs do not increase in total, and the rate of depletion of natural capital (or other forms of capital) does not increase, and yields increase, then the technological development represents an improvement in efficiency of the sort that can be reflected in the model.

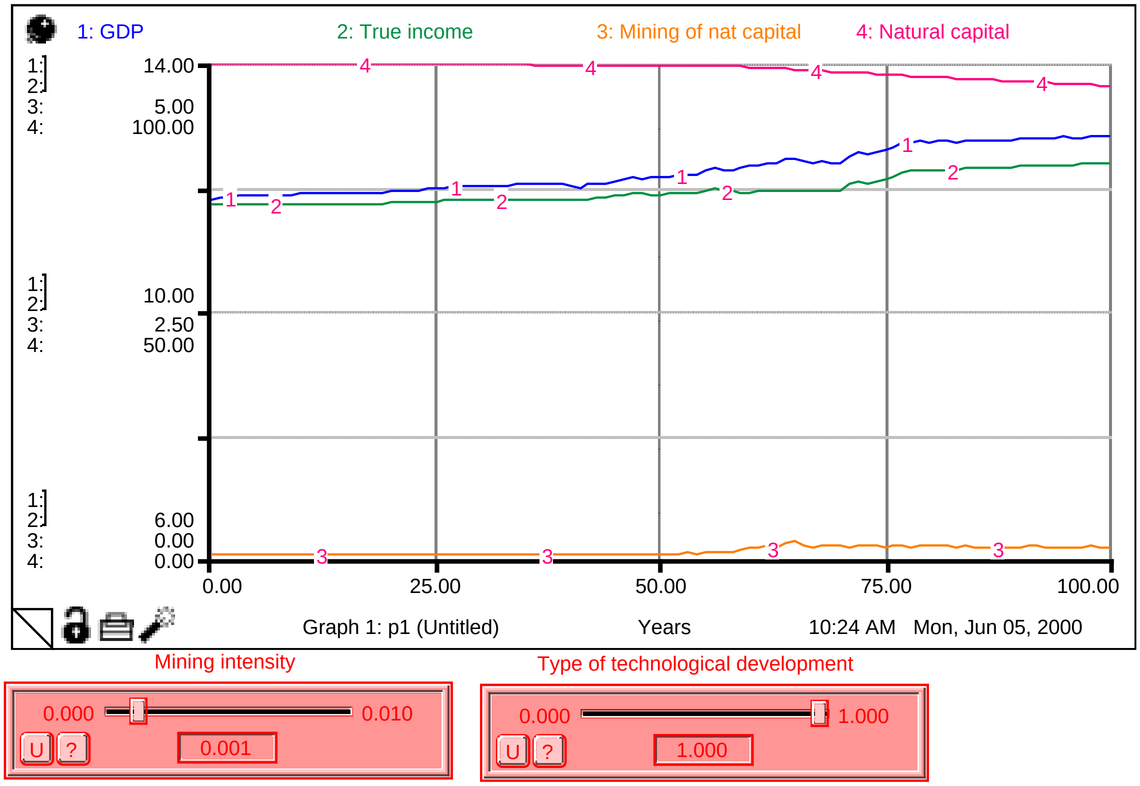

Figure 3: Simple Economy model run as technology increases productivity, and mining of natural capital declines

Important features to note in this graph of this model run are the path that GDP follows, and the underlying causes for the similarities and differences. The generally upward trend for GDP is similar to the first half of the scenario from the model with no technology, but very different in the second half of the scenario. The underlying trends of natural capital, mining, and true income, difficult as they may be to observe in the real-world case, operate quite differently in the second model than they do in the first, even though the initial trend for GDP is very similar in both scenarios. The models, then, provide two very different sets of relationships that will produce similar results initially, but ultimately very different results in the chosen indicator, GDP. Two different hypotheses, with two different ultimate outcomes, fit the initial GDP trend. In the real world, where most of these variables are obscured, a nondeclining GDP might reflect either of these two sets of relationships. The same trend in the traditional indicator may reflect a case of true sustainable development and increasing prosperity, or it may reflect the early part of an overshoot-and-collapse relationship.

IV. Investment in Natural Capital

The technological development approach is one way to manage declining natural capital, and, as in the preceding scenario, efficiency increases may raise output faster than declining stocks reduce output. The model does not, however, allow for investment, or rebuilding, of natural capital. The next modification does.

The model shown in the following diagram is simplified in that all forms of capital of the earlier model – natural capital, manmade capital, and human capital – are combined into one. This simplification makes the diagram easier to understand, even though the primary focus at this point is still natural capital. The two types of technological development of the previous model are also simplified to the efficiency term, which is called productivity. A more important modification, however, is the potential for investment in natural capital. In the model, if gross income is less than a subsistence level of income, then mining for current income makes up the difference. This consumption of natural capital does not constitute true Hicksian income, because it takes from future income. Rather, as in the first scenario of the Simple Economy model, it may be counted in GDP or in some other indicator of gross income.

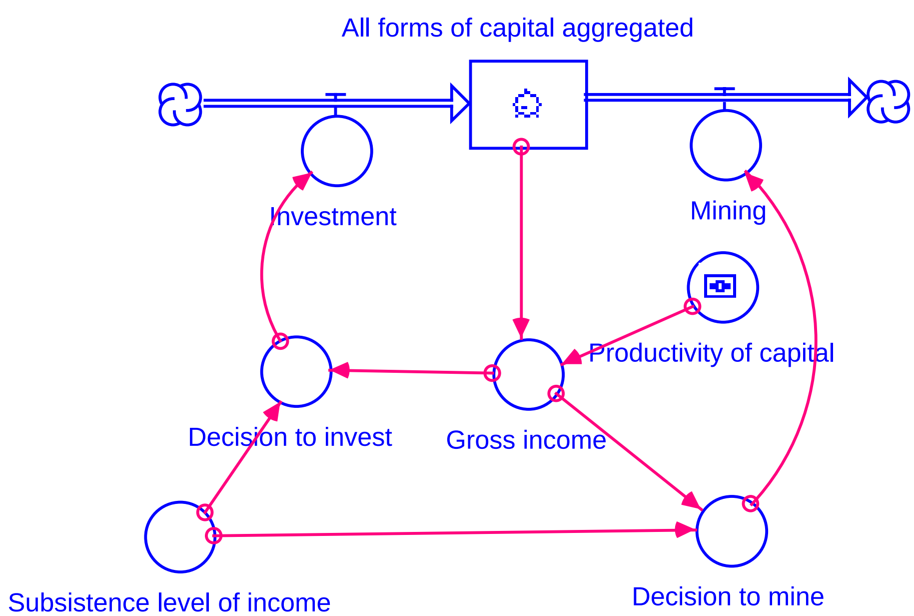

Figure 4: Allowing investment in natural capital

Investment in natural capital comes into play when there is surplus income. According to the model, when gross income is in excess of a subsistence level of income, part of the surplus is invested in natural capital. The augmented stock then yields more income, part of which is then reinvested in natural capital, which then produces more income. The model can yield two positive feedbacks. The first is the destructive feedback of "eating the seed," where mining of natural capital for current income reduces future income, and thereby spurs further mining for current income. The second case is that of increasing prosperity as surplus income is converted into income-producing natural capital.

These two processes – the spiral upward of increasing investment, and the spiral downward of capital consumption – may be mutually exclusive at a small scale, that is, at the level of an individual household or village for example. However, at a larger scale, both positive feedback loops may be in effect simultaneously and independently of one another. The presence of these two feedbacks simultaneously may lead to a bifurcation in the economy, where some individuals in the economy participate in the destructive positive feedback and the downward spiral, and others participate in the positive feedback of increasing prosperity. When aggregate indicators are used to describe the performance of the economy, this bifurcation may occur at a much smaller scale than the scale of the performance indicator. A trend in an aggregate performance indicator, either upwards or downwards, may entirely miss this bifurcating mechanism within the economy.

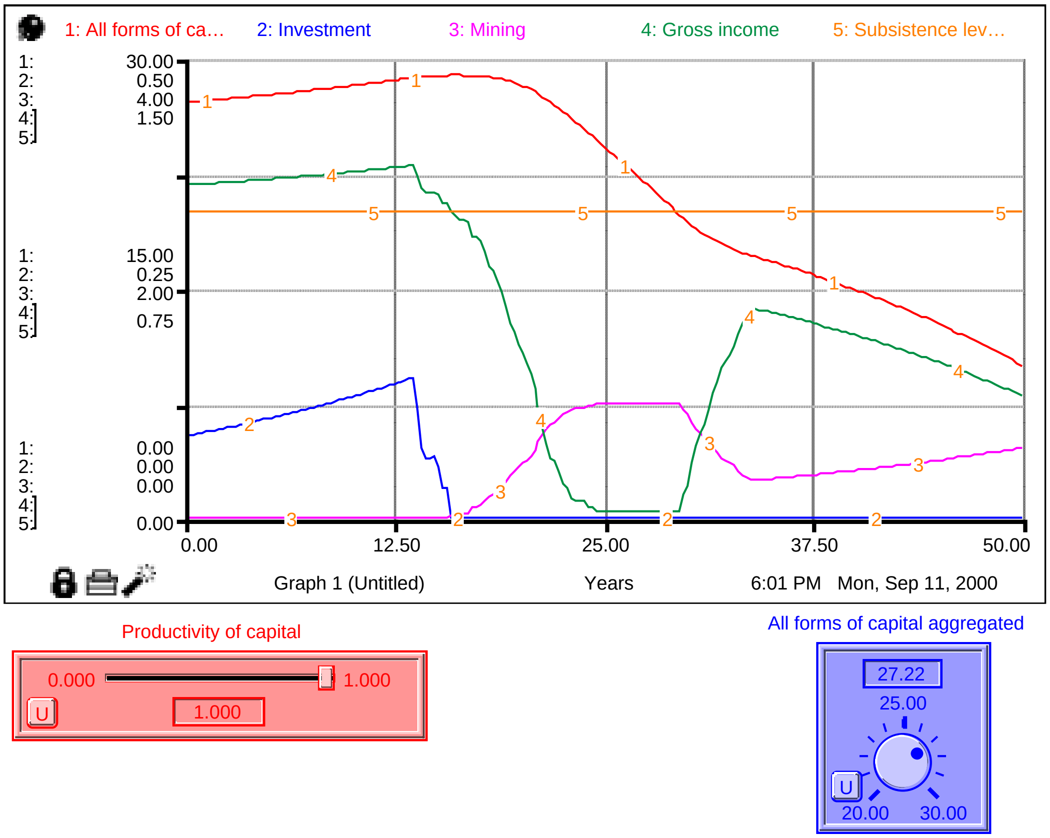

Figure 5: Investment in natural capital shifts to mining when productivity temporarily drops

The above output from the bifurcated economy model illustrates both sets of relationships. Through the first third of the model run, productivity of capital is sufficiently high, and the stock of natural capital is sufficiently high, that the upward spiral holds. In the second third of the run, productivity of capital (the efficiency with which capital is employed) is temporarily reduced. This temporary reduction in productivity draws income down below the subsistence level. At that point, investment drops to zero, and mining takes over. The stock of capital falls, and in the last third of the run, even though the productivity of capital is restored to its original level, the stock of capital is now low enough that the model operates in the destructive positive feedback, the tightening downward spiral of capital mining. Mining of natural capital for current consumption leads to a smaller stock of capital, which compromises future income. This is one form of overshoot and collapse.

The behavior of this model tends toward one of two positive feedbacks, either a spiral up, or a spiral down. The spiral down is related to mining to meet immediate basic needs. It is the nature of these feedbacks that they are self-steering, and that both type of feedbacks may occur simultaneously in a small area. The spiral up of increasing prosperity reflects a built-in understanding that some part of income in excess of a subsistence level will be reinvested in natural capital, or other forms of capital. However, in the real world, it is not necessarily the case that surplus income will be reinvested in capital, natural capital in particular. Other real-world scenarios include investment necessary to meet basic needs and perhaps a bit more, but no additional investment. Investment may be necessary to protect earlier investments and maintain the current status of capital, but not to expand or augment the capital beyond that point. Many other factors may impinge on investment in natural capital. Knowledge and technical skills, concern over the status of capital, risk, and the opportunity cost of one's time may all have a role. The expanded Primary Economy model addresses each of these sets of relationships in turn.

The Full Primary Economy Model

The full Primary Economy model to date includes seven sectors. The core of the model, shown below, allows for investment in, and mining of, capital. Although the model specifies all forms of capital as an aggregate, the emphasis throughout the process of model development is on natural capital. In the earlier models, investment or mining is dependent on a surplus or deficit of income. The same applies in the expanded model, but other variables come into play. A surplus of income is still necessary for investment, but a history of investment tends to spur further investment. The history-of-investment variable stores 10 years of investment history. When conditions are otherwise suitable for investment, this variable determines in part the magnitude of investment. The investment history, and its relationship to current investment, attempts to capture some of the causes of investment that are not explained in other sectors. Some investments are sunk costs in that they cannot be directly divested and re-invested elsewhere. Any fertilizer that goes into a field, for example, cannot be directly extracted and used elsewhere. It may, however, be recovered subsequently as a crop. In the meantime, subsequent invests may be necessary to protect the initial investment of fertilizer. It is this investment related to earlier investment that the history-of-investment relationship describes.

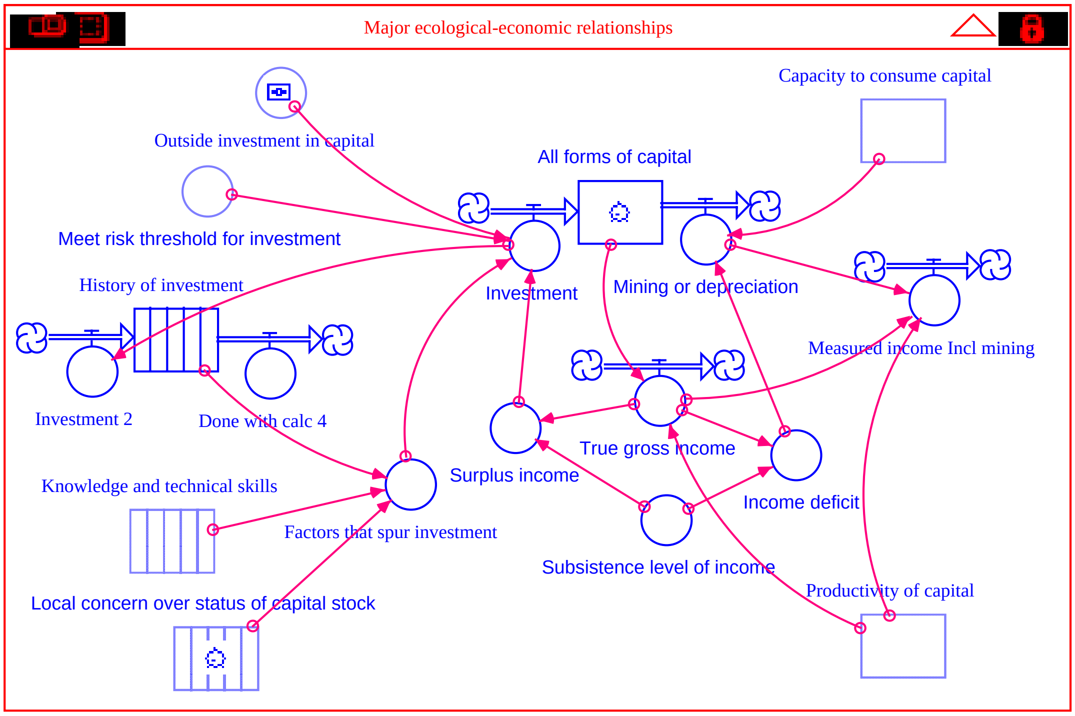

Figure 6: Major ecological-economic relationships within the Primary Economy model

Within the core model, several components enter from other sectors of the model. In addition to the history of investment, knowledge and technical skills bear on the magnitude of investment. Similarly, local concern over the status of the capital stock has bearing. Several risk-related variables determine whether the potential payoff from the investment, weighted by all the risks of loosing the investment, justifies the certain expense. Therefore, there are two thresholds that must be met for investment to occur. First, there must be income in excess of a subsistence level of income. Second, the potential investment must pass a benefit-cost test; the risk-weighted anticipated benefits of the investment must be greater than the known costs of the investment. Once the two thresholds are met, the magnitude of the investment is determined by the amount of surplus income, knowledge and technical skills (from another sector of the model), and concern over the status of capital (also from another sector of the model).

Technology, as in an earlier version of the model, can increase the efficiency with which natural capital is used, or increase the capacity to mine natural capital, or both. It is calculated in its own sector. Income is calculated two ways: true Hicksian income, and gross income including mining. Consistent with the earlier version, efficiency improvements are counted in income. The remaining sectors of the model feed into this core sector of investment in, and mining of, natural capital.

Other Major Relationships Within the Model

Once the conditions for investment are met, knowledge and technical skills, and local concern over the status of the capital stock determine in part the magnitude of investment. The development of knowledge and technical skills is part of a feedback loop that spurs skill development only when skills are well-suited to a given need. The degree to which learned skills are useful determines in part the degree to which individuals pursue the development of additional skills. In addition, the opportunity cost of one's time is related to skill development, in that the greater the opportunity cost of one's time, the less inclined one will be to spend time seeking out new skills. This feedback comes into play when increasing prosperity raises the opportunity cost of one's time, and thereby tends to effectively raise the cost of seeking out new skills. Conversely, falling opportunity cost opens a possibility to introduce new skills to individuals at low cost. A further relationship flows from the demographic sector. There, an increase in the early death fraction opens a knowledge and generation gap that tends to impede the transfer of skills from one generation to the next.

Knowledge and technical skills feed into local concern over the status of the capital stock. A high early death fraction from the demographic sector tends to dampen concern over the status of capital. The reasoning is that a short anticipated lifespan tends to effectively increase discount rates as individuals turn toward meeting immediate needs rather than addressing longer-term concerns.

The risk sector includes several important feedbacks, including feedbacks with other sectors. One of the criteria for investment is that the expected payoff, weighted for all risks and risk aversion, must be greater than the known cost. Variables related to cost include the opportunity cost of one's time, and costs that accrue as a result of efforts to manage risk. These efforts at managing risk include diversification, and shifting investment toward easily liquidated capital when land tenure is weak. The model counts several other types of risk: risk to social stability, weather, and price fluctuations. Age and gender have an effect on access to capital, so those demographic variables are related to the probability of receiving a given price. One's risk aversion is inversely related to surplus income, and weighs against investment when there are risks.

Although the demographic sector's diagram seems complicated, the core of the sector is quite simple. Births are recorded, then individuals are recorded in each of three age classes, then they die. Early deaths occur in each of the age classes. Gender mix and average age is recorded for each age class, and for the total population. The early death dynamics can be left off, or turned on to simulate, e.g., HIV/AIDS.

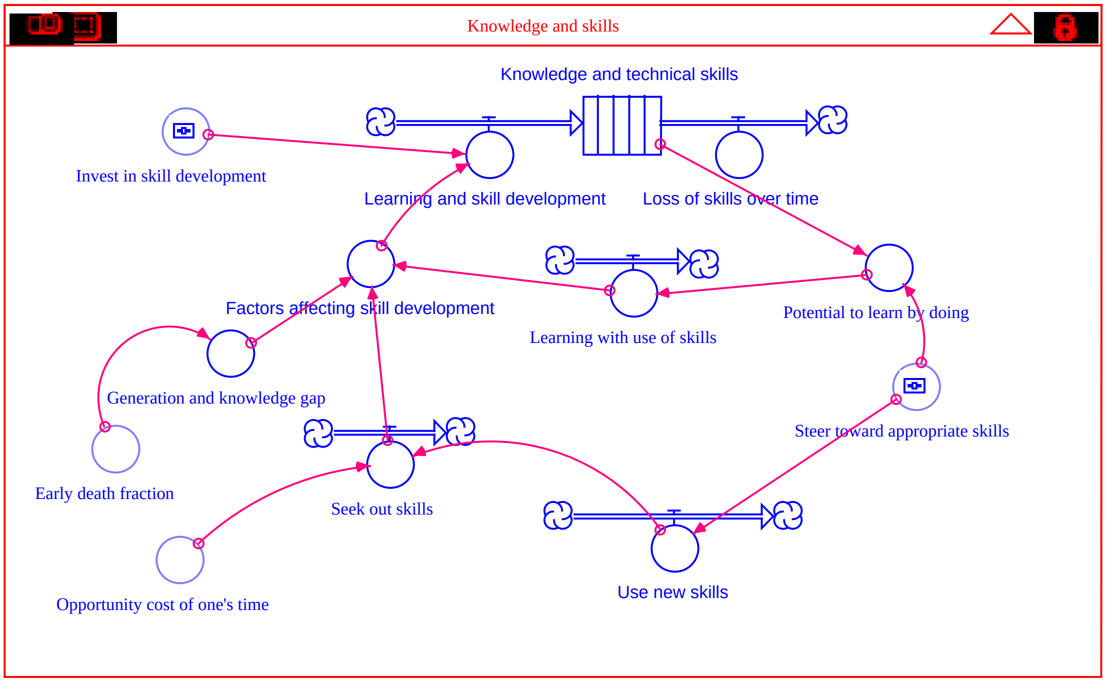

Figure 7: Knowledge and skills sector

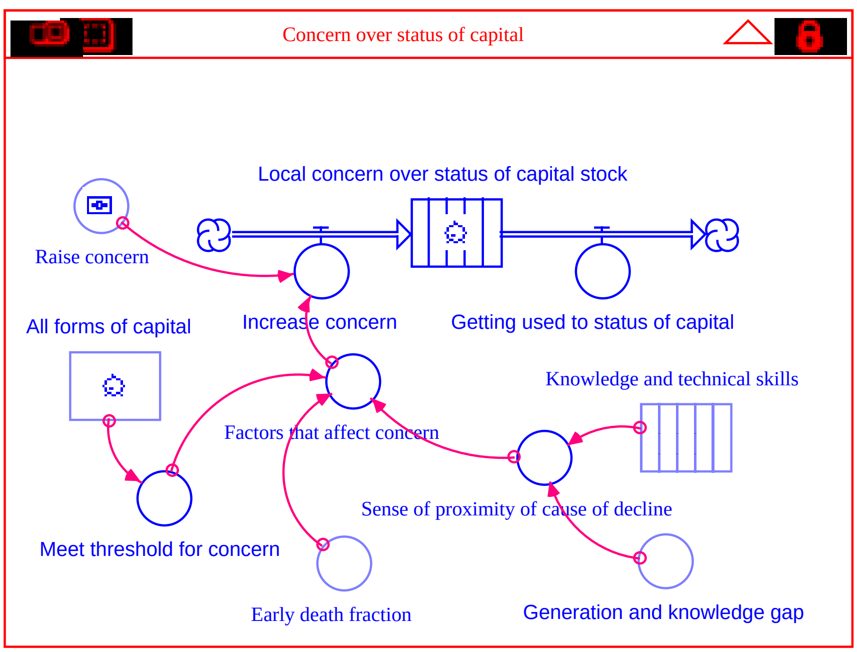

Figure 8: Concern over status of capital

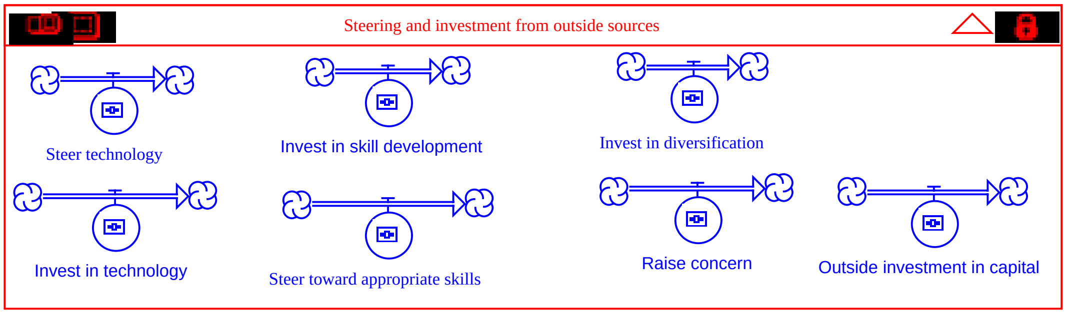

Figure 9: Steering and investment from outside sources

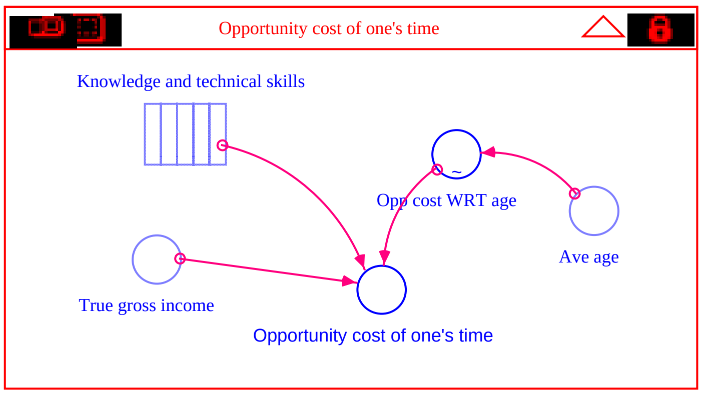

Figure 10: Opportunity cost of one’s time

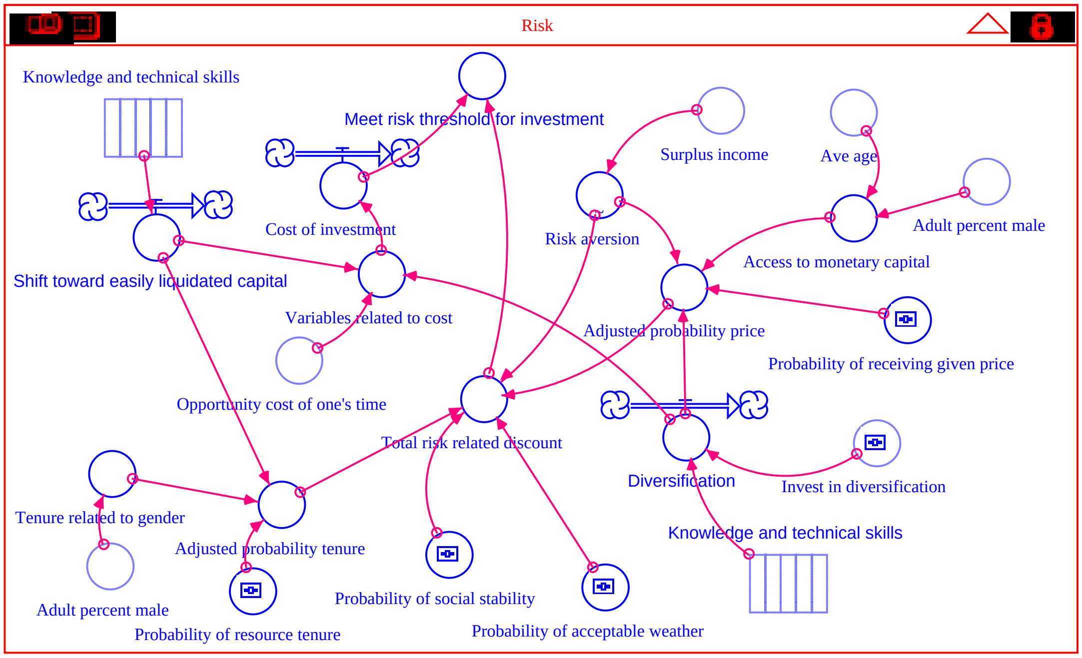

Figure 11: Risk

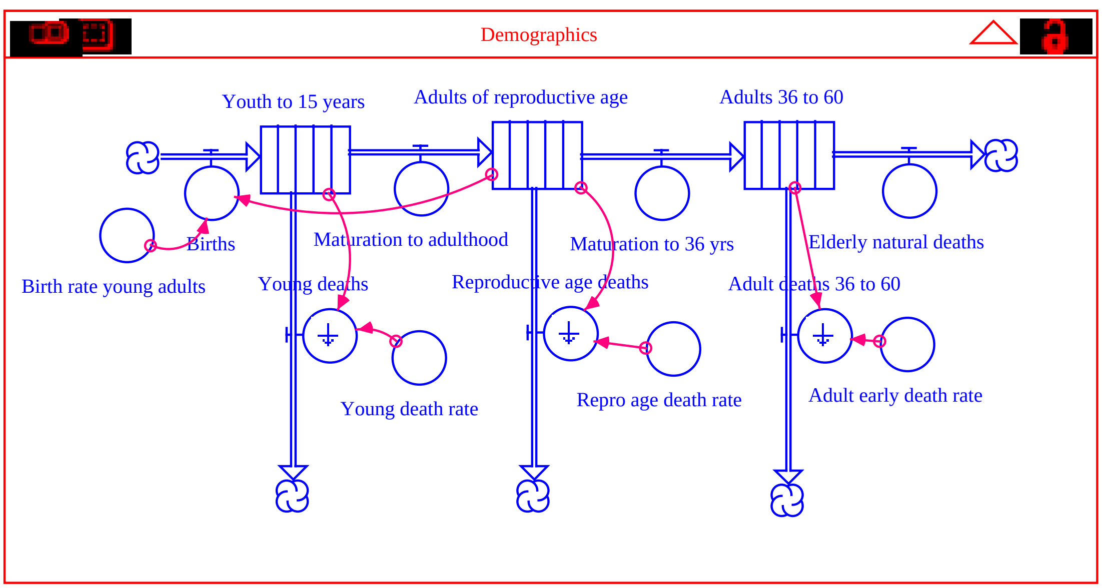

Figure 12: Demographic relationships (simplified diagram)

Diminishing returns are generally modeled in one of two ways. Unbounded diminishing returns generally employ the Cobb-Douglas production function of the form $Y=A^aB^bC^c$, where Y is output; A, B, and C are inputs; and a, b, and c are factor shares, which can be interpreted roughly as a weight, or the sensitivity of output to changes in the associated input. In all cases, a, b, and c sum to 1 indicating constant returns to scale. In short, proportional increases in A, B, and C will produce a proportional increase in Y. However, a given increase in either A, B, or C, will yield less than a proportional increase in Y.

Bounded diminishing returns generally employ a Michaelis-Menton relationship of the form $Y=a+Y_{max}\ (X/(S+X))$, where Y is output between a and $a+ Y_{max}$, Y_{max} is a constant, X is input, and S is the half-saturation constant, the level of X which yields the output $(a+ Y_{max})/2$.

Model Runs

All the previous relationships of the earlier models still apply to the expanded Primary Economy model. The following model runs illustrate a few features of the model that go beyond the features of the earlier models. In the first run, increasing prosperity fuels investment that grows the stock of natural capital, which raises income and increases prosperity further. This increasing prosperity increases incomes and, working through that sector of the model, also increases knowledge and skills. The combination of knowledge and skills facilitate investment, and thereby increase incomes. These skills also open opportunities for bringing in income elsewhere in the economy at the same time that the increased income effectively increases the opportunity cost of one’s time. As that opportunity cost rises, the alternatives look more attractive than does investment in natural capital, and those investments fall off.

In the model, this fall-off of investment works through the opportunity cost variable, which feeds into the total cost of investment, which eventually makes further investment unprofitable. The relationship is not predictive, in that there are other variables at play that may keep investment going, but it may be important in that it helps explain why an increase in income may lead individuals to turn away from maintenance of natural capital.

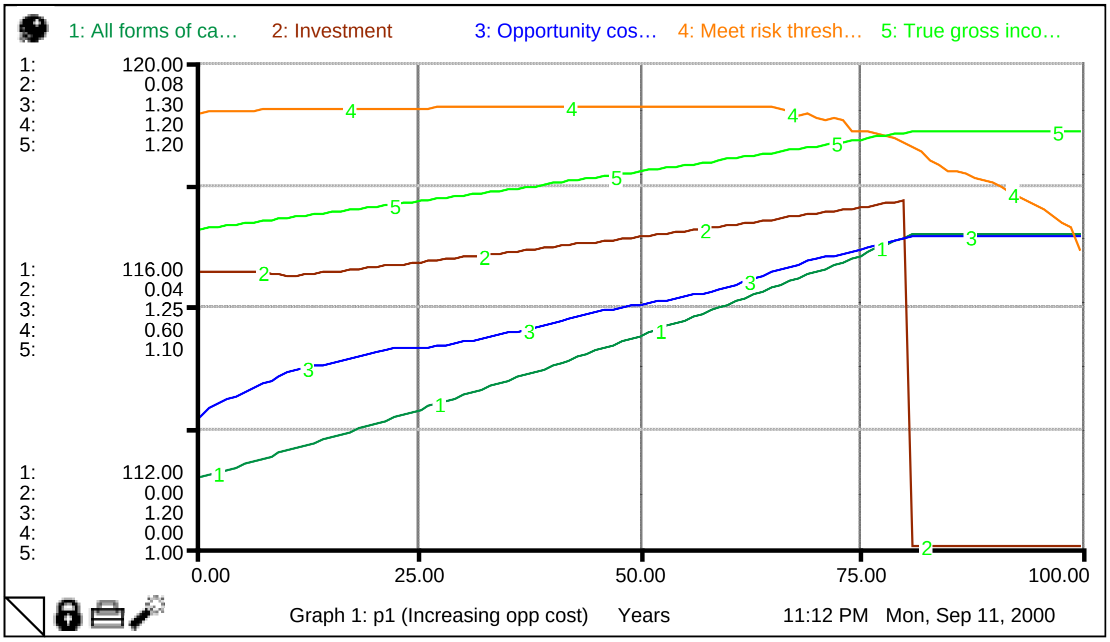

Figure 13: Investment die-off

This relationship may hold at particular income levels and not others, and when viewed with aggregate statistics, the overall trend may be opposite the relationship described here. That is, a general increase in income within a given region may correlate with improved maintenance of natural capital, although the general trend may mask specific cases where rising opportunity cost of people's time leads them to reduce their efforts at maintaining a productive stock of natural capital. This relationship also begs the question of the relative private benefits to be derived from investing in natural capital and drawing a sustainable income from the stock of capital, vs. mining natural capital for income. In the case where mining raises income enough to substantially raise one's opportunity cost of time, the more labor-intensive maintenance of natural capital may fall by the wayside. In this case, mining of natural capital is spurred not by poverty, as illustrated in the earlier iteration of the model, but by growing private affluence that makes one's time too valuable to invest in maintaining natural capital.

These relationships are especially important when attempting to understand the relationship between wealth, or income, and the maintenance of productive natural capital. At a sub-subsistence income, where mining is necessary to raise an income to a subsistence level, it is that poverty that drives mining. As incomes rise, the relationship is more complicated, in that surplus income allows for investment, but at certain levels of income, and where there are opportunities to do so, walking away from maintaining natural capital, or turning toward mining of another sort, may be rational choices.

One possible scenario involves rapid consumption of natural capital, accumulation of the excess income, and reinvestment in other forms of capital to yield a higher, more nearly sustainable income. Along these lines, Reardon and Vosti (Reardon and Vosti 1995) envision a scenario where the poor might mine the soil through intensive cropping without investing in soil conservation, and then use the profits to build capital elsewhere and move away from agriculture. In this way, long-term pressure on the land could be reduced.

The next graph illustrates a "climb out" scenario, where judicious application of technology, or improved resource efficiency of any sort, turns a mining scenario into an investment scenario. At the start of the model run, the downward spiral of mining holds as natural capital is increasingly depleted. A one-time introduction of increased technological efficiency raises income above a subsistence level, and allows for investment that grows the stock of natural capital. In this scenario, the improvement in technological efficiency is a one-shot deal; there is maintenance of that new level of efficiency, but no continuing increase.

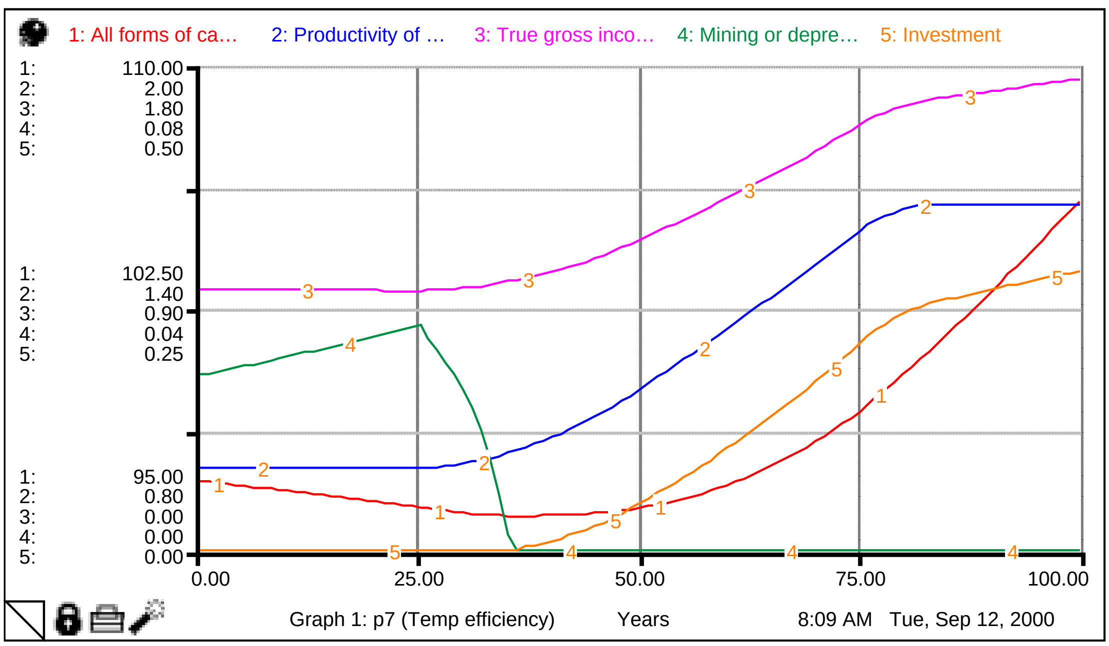

Figure 14: A one-time technology boost

In the long run, this is a case of strong sustainability. In the weak sustainability case, technology may help make up for depletion of natural capital by increasing the productivity of remaining capital. In the scenario illustrated here, however, that relationship holds only during the period of transition. After the initial introduction of efficiency-improving technology, growth of natural capital carries the subsequent increase in incomes. The stock of natural capital is not replaced by increases in technological efficiency, but augmented instead.

Elusive as the one-time technology boost scenario may be in parts of Africa, it may constitute the most realistic scenario for climbing out of a downward spiral of mining and depletion. To use increasing technological efficiency to outpace mining or depletion of natural capital requires a continuing input of technology, in this case, assistance. In the scenario illustrated above, introducing increased efficiency is a one-shot deal, with subsequent increases in income coming from local investments in natural capital, not increased technological efficiency from outside sources. The scenario begs basic questions about what sort of technology can be inserted that way, and how to hold it in place over time.

The following three graphs show basic trends from the demographic sector. In the first graph are basic population scenarios for each of the three age classes. In this case, there are no early death dynamics, no HIV/AIDS; and the population of each age class grows accordingly. In the second graph, the early death dynamics are still not engaged. Instead of relative populations of each age class, the percent of the total population within each class is plotted. In the third graph, early death dynamics are turned on, and the percentage of the population in each age class is again reported. The notable difference between the second and third graph is the drop in percentage of the population in the 16-35 age class. Essentially, the early death dynamics, in addition to bending down the population trends as a whole, have disproportionately taken the middle out of the age distribution.

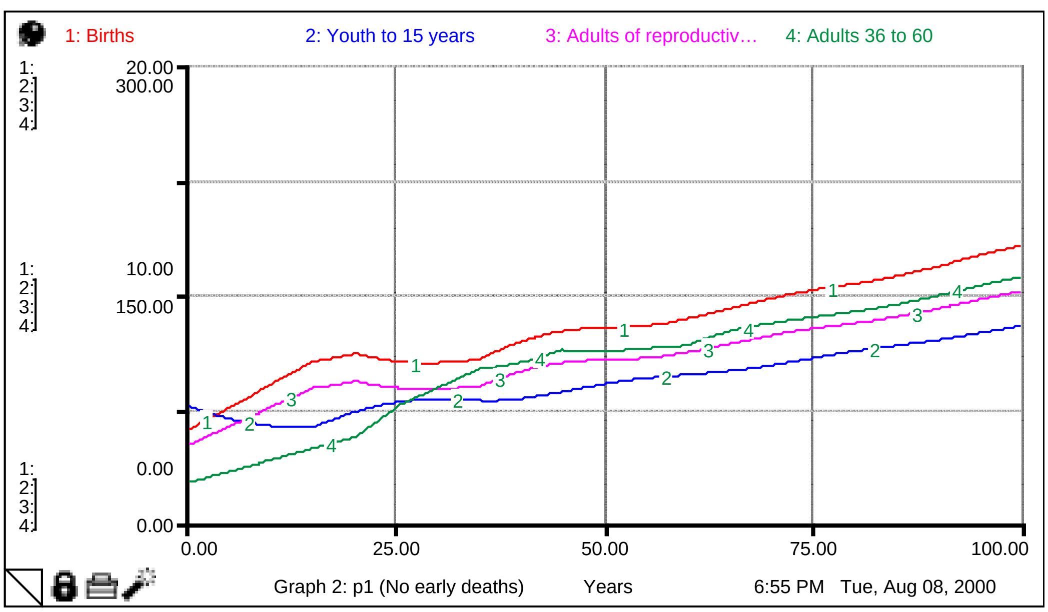

Figure 15: Population trends with no early deaths

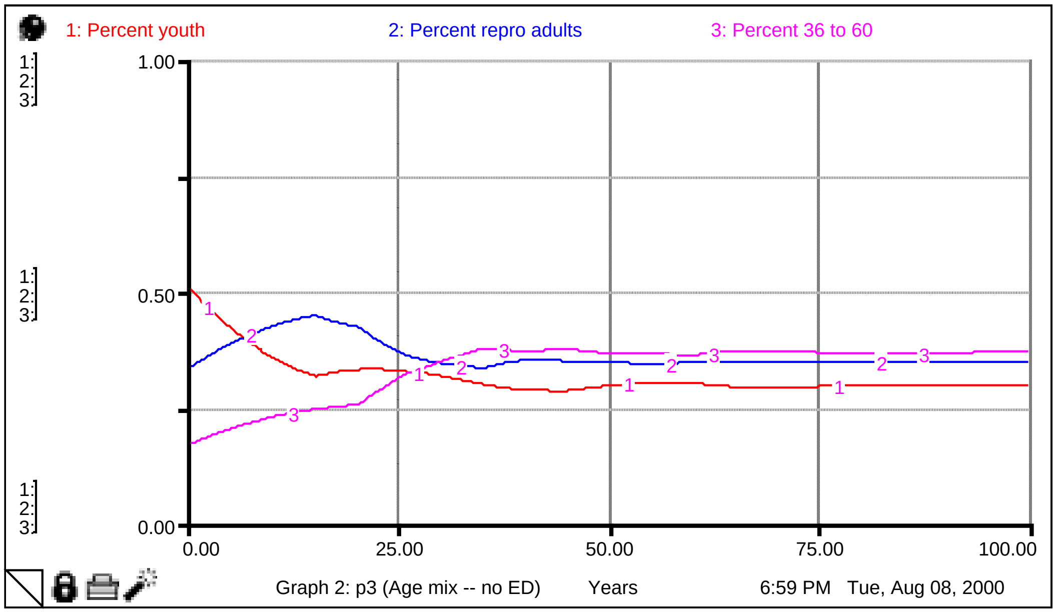

Figure 16: Age mix with no early deaths

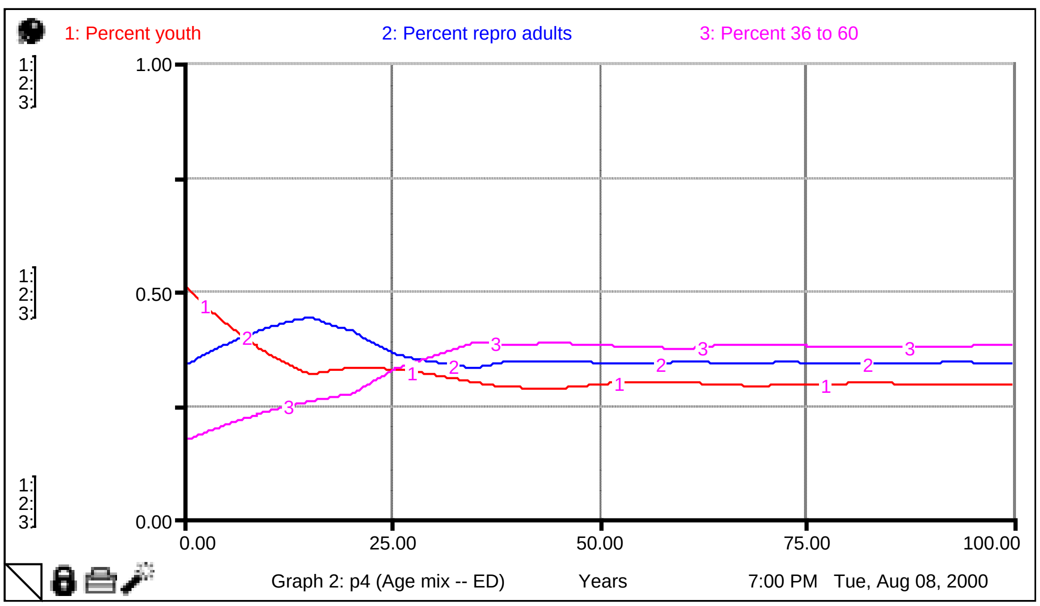

Figure 17: Age mix with early deaths

The demographic variables directly enter the model in four other sectors. Access to monetary capital, and land tenure within the risk sector are related in part to age and gender of the borrower, and gender of the landowner. Early deaths as a result of HIV/AIDS shorten one's time horizon and tend to reduce concern over the status of natural capital. Age, and commensurate skills, similarly affect the opportunity cost of one's time. Early deaths contribute to a generation and knowledge gap that in turn impedes the development of skills, and their transfer from one generation to the next.

The interrelatedness of these variables can be very intricate, as one variable affects others that work their way through a feedback loop to the original variable. It is these feedbacks, where the emphasis is on the causal relationships among variables, rather than the statistical relationships among variables, that distinguishes this modeling environment from the more traditional approaches involving more easily measured indicators. The simulation modeling environment and the participatory modeling approach offer a way to explore these intricacies among variables. The insights to be gleaned from the model accrue primarily to the people who develop the model; as here, it is often difficult to follow the full logic of the model after the model is written. Therefore, it bears mentioning again the importance of a participatory approach to developing the model.

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Annex 1: Additional Information About the Stella Modeling Environment

A save-disabled demonstration version of the Stella simulation modeling package, and Stella tutorials, are available on the High Performance Systems Inc. website.

High Performance Systems website home page:

http://www.hps-inc.com/index.html

Stella free demo version, and demonstration models:

http://www.hps-inc.com/edu/stella/demo_gate.htm

Stella/ithink tutorials:

http://www.hps-inc.com/customer%5Fcenter/kb/webhelp/toclist.htm